SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

1. REPORT NUMBER	2. GOVT
4. TITLE (and Subtitle) Annual Report for work on "Liquid and Solid Ion Plasmas" ONR Contract N00014-92-F-0038	5. TYPE OF REPORT & PERIOD COVERED Annual October 1, 1991 - September 31, 1992
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D.J. Wineland and J.J. Bollinger	8. CONTRACT OR GRANT NUMBER(s) N00014-92-F-0038
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Institute of Standards and Technology Time and Frequency Division, 847 Boulder, CO 80303	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Physics Program Office, 800 N. Quincy Arlington, VA 22211	12. REPORT DATE 10/22/92
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

nonneutral plasma; one component plasma; strongly-coupled plasma; liquid and solid plasma; plasma distribution functions; Penning trap; laser cooling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Atomic ions which are stored in electromagnetic fields are an example of nonneutral plasmas. Laser techniques allow control of plasma angular momentum and provide plasma cooling to temperatures much less than 1K. Using imaging techniques, plasma spatial information is achieved. Laser spectroscopic techniques allow measurement of plasma velocity distribution functions. Liquid and solid behavior of ion plasmas is studied.

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Summary of work on
"LIQUID AND SOLID ION PLASMAS"
(FY '92)

submitted to

Office of Naval Research

ONR Contract No. N00014-92-F-0038

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ONR SUMMARY ON "LIQUID AND SOLID ION PLASMAS" (FY '92)

I. INTRODUCTION

In these experiments, performed at the National Institute of Standards and Technology, Boulder, Colorado, atomic ions are stored in combinations of electric and magnetic fields. The resulting nonneutral ion plasmas can be viewed as one component plasmas where global equilibrium is obtained over long times (many hours). The use of atomic ions allows laser cooling, where the temperatures of the plasma can be reduced to 10 mK or less. For the densities typically achieved (up to 10^{10} cm^{-3}) the plasmas become strongly coupled with coupling parameters Γ in excess of 100. The same lasers can be used to impart angular momentum to the plasma which provides a convenient method to control the density. The laser light which is scattered from the ions can also be observed in an imaging camera so the photographs and real time videos of the plasma can be made. Finally, by measuring the spectra of certain transitions in the ions, we can extract Doppler shifts and Doppler broadening which allows us to determine plasma temperature and rotation frequencies (and therefore, densities). Current efforts are devoted to applying these techniques to the measurement plasma dynamics and spatial correlations in ion plasmas.

1. PENNING TRAP STUDIES

a. Experiments to search for modes in electron plasmas stored in a cryogenic Penning trap.

Under conditions where the (Debye length) << (plasma dimensions) << (trap dimensions), the modes of a nonneutral Penning trap plasma are exactly calculable and, for a given trap axial and cyclotron frequency, depend only on the rotation frequency or, equivalently, the density of the plasma. Knowledge of the plasma mode structure may be important for storing charged particles at high density as excitation of certain modes by static field asymmetries inhibits the attainment of large densities. In addition, observation of the mode frequencies may provide a nondestructive diagnostic technique for determining the density and shape of Penning trap plasmas when other techniques are not available, such as with positron and antiproton plasmas or plasmas of ions which do not have a convenient transition for laser scattering.

For this reason we undertook a study of the modes of electron plasmas stored in a cryogenic Penning trap; this study was conducted by Dr. Carl Weimer using a trap he built to study the nonlinear excitation of the cyclotron motion of a single electron. The electrons are detected by their image currents in one of the endcap electrodes. A spectrum analysis of the image currents in the neighborhood of the trap axial frequency is shown in Fig. 1 for a plasma of about 40 000 electrons. The broad resonance is due to noise currents in the resonant circuit connected to the endcap electrode. The narrow spectral features superimposed on the broad resonance are collective modes of the electron plasma. For example, the third narrow

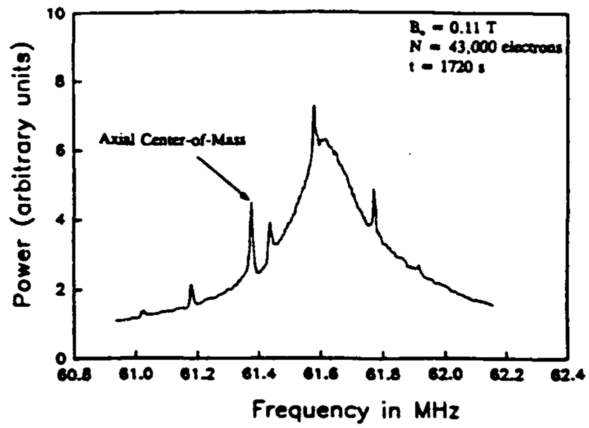

Fig. 1: plasma modes near the axial frequency

signal from the bottom is the axial center of mass mode. The other narrow features are identified with $\ell \geq 2$ modes. Higher order modes near the trap axial frequency occur at low rotation frequencies where the plasma is shaped like a pancake. In principle our image current detection should only be sensitive to axially symmetric modes. However, if there is a nonlinear coupling of the modes to the center-of-mass modes, then some of the asymmetric modes could be detectable. A sideband cooling technique previously developed to reduce the magnetron radius of a single, trapped electron was used on the electron plasmas. This technique apparently increases the rotation frequency and density of the electron plasma. After application of the sideband cooling technique, only the axial center of mass mode is visible on the spectrum analyzer. After a period of time that depends on the magnetic field, the other narrow signals appear in the spectrum of the image currents. These signals drift across the spectrum from low to high frequency. This type of behavior is expected for some of the ℓ-m = 1 and ℓ,m=0 modes if the rotation frequency is decreasing in time. In this way it appears possible to follow the expected decrease of the rotation frequency with time (presumably caused by static field errors). Fig. 2 shows the evolution of the detected mode frequencies with time.

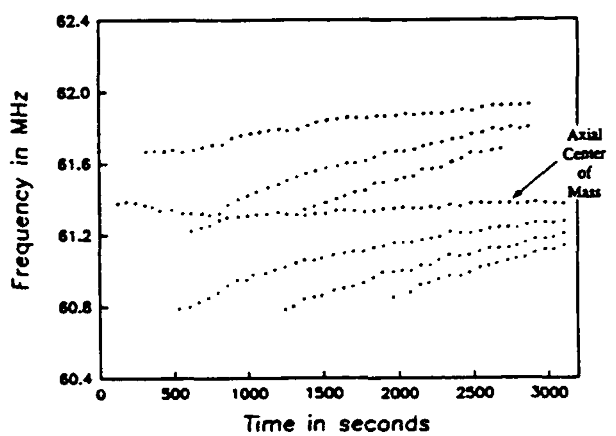

Fig. 2: time evolution of mode frequencies

So far these measurements have been done at magnetic fields of 0.1, 0.25, and 1.5 T. These results are currently being written up.

b. Feasibility of laser-cooled positron source.

We have examined theoretically the feasibility of producing a sample of cold (≤ 4 K), high-density ($\simeq 10^{10}/cm^3$) positrons which are contained in a Penning trap. These positrons may be useful as a source for antihydrogen production (by passing antiprotons through the positrons and relying on antihydrogen production through 3-body recombination), as an example of a quantum plasma ($\hbar\omega_p \geq kT$), and as a possible means to produce a bright beam of positrons by leaking them out along the axis of the trap.

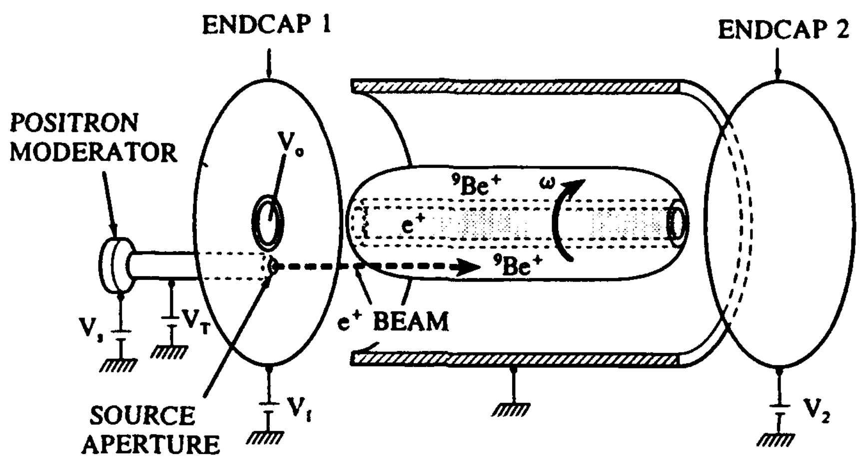

Fig. 3: Schematic diagram of positron accumulator

We assume $^9Be^+$ ions are first loaded into the trap and laser-cooled to $\simeq$ 10 mK where they form a uniform density column centered on the trap axis. Positrons from a moderator are then injected into the trap along the direction of the magnetic field (axial direction) through an aperture in one endcap of the trap so that they intersect the $^9Be^+$ column. Positron/$^9Be^+$ Coulomb collisions extract axial energy from the positrons preventing them from escaping back out the entrance aperture. Cooling provided by cyclotron radiation and sympathetic cooling with the laser cooled $^9Be^+$ ions causes the positrons to eventually coalesce into a cold column along the trap axis with the $^9Be^+$ ions forming a hollow column which surrounds the positrons. We have estimated the efficiency for capture of the positrons (close to 100% for a $^9Be^+$ plasma of 10 cm length) and limiting densities and temperatures of the resulting positron column. Experimental results which are relevant to this scheme are the observation of spatial separation of two charge species and the cooling transferred from the laser-cooled species to the other species.

c. Assembly of coupled trap apparatus completed.

The coupled trap uses two Penning traps which share a common endcap. In one trap a plasma of ions which can be laser cooled (in our experiment, $^9Be^+$)

is loaded and laser cooled to low temperature. In the other trap is loaded another charged species (which cannot normally be laser cooled - in our experiment, electrons). The voltages on the two traps are adjusted to give identical center of mass axial frequencies. In this case, the induced image currents in the shared endcap couples the electrons and the cold $^9Be^+$ ions. In this way the coupled trap can be used to cool an electron plasma to below 4 K. This trap will be operated at cryogenic temperatures and is the most complicated trap that we have attempted to assemble. First tests of this apparatus are now underway.

d. New Penning trap construction.

The construction of a new, large Penning trap with improved diagnostic capabilities for the study of nonneutral $^9Be^+$ plasmas has continued. Technical problems arose during the construction of the original trap design. In this first design the trap was formed from a single piece of quartz to insure the axial symmetry of the different electrodes. Vacuum deposition of titanium on the quartz provided a metallic surface. Etching away the titanium at the proper locations would then create individual electrodes. Problems arose with the quartz chipping and with the removal of titanium on the inside of the quartz bore. Therefore, a new experimental trap has been designed and is under construction. The trap is being made out of OFHC copper and uses more conventional techniques for assembly and construction.

The optics for imaging the ion fluorescence both perpendicular and parallel to the magnetic field has been designed. Fabrication of the optics has begun. John Bollinger is now spending most of his time on assembling this experiment.

e. Detailed paper on the mode studies.

We have combined our work with that of Dan Dubin at UCSD in a detailed paper on the modes of a nonneutral ion trap plasma. The completion of this paper was delayed in order to correct the design for the new Penning trap, however the paper is now complete. It emphasizes the importance of the modes for high density confinement (i.e., excitation of certain of the modes by static fields can impede the attainment of high densities) and the usefulness of the modes as a diagnostic tool.

2. LINEAR PAUL TRAP STUDIES (FY '92)

a. First results of linear rf trap reported

The results from the first experiments on small plasmas contained in a linear Paul (rf) trap have been written up and reported: "Ionic crystals in a linear Paul trap," M. G. Raizen, J. M. Gilligan, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. A45, 6493 (1992) and "Linear Trap for High Accuracy Spectroscopy of Stored Ions," M. G. Raizen, J. C. Bergquist, J. M. Gilligan, W. M. Itano, and D. J. Wineland, J. Mod. Optics 39, 233 (1992). These reports dealt with the basic design features of the trap and reported agreement of simple crystal structures observed in the traps with structures

calculated theoretically.

b. Modification of linear trap for larger plasmas

Two primary modifications have been completed for allowing larger ion plasmas to be studied in the linear trap.
(1): We identified an rf loss mechanism in the trap structure which prevented high rf voltages from being applied to the trap. (Higher rf voltages imply higher plasma densities.) We found that rf currents in a thin surface coating of titanium on the ceramic support structure gave rise to relatively large rf loss. We have now corrected the problem and have been able to obtain significantly larger voltages and ion densities.
(2): Small 194 nm laser power ($\simeq 5\ \mu W$) for laser cooling in previous experiments on $^{199}Hg^+$ plasmas prevented the cooling of large plasmas ($N > 100$). Recently, by using a different nonlinear crystal (BβO) in the summing stage of the 194 nm generation, Jim Bergquist has succeeded in obtaining about 100 times larger 194 nm power - we anticipate this will significantly increase our ability to laser-cool large $^{199}Hg^+$ plasmas.

c. Cryogenic linear rf trap under construction

In the $^{199}Hg^+$ rf trap experiments, simultaneous storage of $^{199}Hg^+$ ions and extraneous ion species from background gas can cause "rf micromotion" heating of the $^{199}Hg^+$ ions and limit the size of ion plasmas that can be laser cooled. The storage of extraneous ions occurs primarily because background gas ions are created along with the $^{199}Hg^+$ ions. By going to much better vacuum by use of cryopumping, we hope to reduce considerably the fraction of extraneous ions that are loaded. A linear trap of design similar to that used previously is under construction. It will be operated in a liquid He (4 K) environment which should reduce the background gas pressure by at least 4 orders of magnitude.

II. PUBLICATIONS ETC., FY '92

a. Submitted papers (not yet published):

1. "Laser-Cooled Positron Source," D. J. Wineland, C. S. Weimer, and J. J. Bollinger, proc. of the Anti Hydrogen workshop, Munich, July 30-31, 1992, submitted.
2. "Electrostatic modes of an ion trap plasma," J. J. Bollinger, D. J. Heinzen, F. L. Moore, W. M. Itano, D. J. Wineland, and D. H. E. Dubin, submitted.

b. Papers published in refereed journals:

1. "Ionic crystals in a linear Paul trap," M. G. Raizen, J. M. Gilligan, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. A45, 6493 (1992).
2. "Linear Trap for High Accuracy Spectroscopy of Stored Ions," M. G.

Raizen, J. C. Bergquist, J. M. Gilligan, W. M. Itano, and D. J. Wineland, J. Mod. Optics 39, 233 (1992).

3. "Low order modes of an ion cloud in a Penning trap," J. J. Bollinger, D. J. Heinzen, F. L. Moore, W. M. Itano, and D. J. Wineland, Physica Scripta, 46, 282 (1992).

c. Books or Chapters submitted:

1. "Experimental results on normal modes in cold, pure ion plasmas," J. J. Bollinger, D. J. Heinzen, F. L. Moore, C. S. Weimer, W. M. Itano, and D. J. Wineland, Proc. Int. Conf. on The Physics of Strongly Coupled Plasmas, Rochester, 1992, ed. by Van Horn and Ichimaru, submitted.
2. "Recent Experiments on Trapped Ions at the National Institute of Standards and Technology," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, F. L. Moore, J. M. Gilligan, M. G. Raizen, D. J. Heinzen, C. S. Weimer, and C. H. Manney, Proc. of the Enrico Fermi Summer School on "Laser manipulation of atoms and ions," July, '91, Varenna, Italy, submitted.
3. "Laser Cooling of Trapped Ions," W. M. Itano, J. C. Bergquist, J. J. Bollinger, and D. J. Wineland, ibid.

d. Printed Technical reports and non-refereed papers:

1. "Trapped Ions and Laser Cooling III," NIST Technical Note 1353, ed. by J. C. Bergquist, J. J. Bollinger, W. M. Itano, and D. J. Wineland, (U. S. Government Printing Office, Washington, 1992).

e. Invited presentations at workshops or Prof. Soc. meetings:

1. Dave Wineland, FACCS conf. on Chemical methods, Anaheim, Oct. '91.
2. Dave Wineland, AAAS meeting, Chicago, Feb. '92.
3. Dave Wineland, Plasma workshop, Irvine, July, '92, (summary talk)
4. John Bollinger, Plasma workshop, Irvine, July, '92, (ion plasmas)
5. John Bollinger, Strongly coupled plasmas, Rochester, Aug. '92.

f. Other presentations at workshops or Prof. Soc. meetings:

1. Dave Wineland, APS plasma annual meeting, Tampa Bay, Nov. '91.
2. Fred Moore, Plasma workshop, Irvine, July, '92, (coupled trap)
3. Carl Weimer, Plasma workshop, Irvine, July, '92, (electron modes)
4. Fred Moore, ICAP, Munich, Aug. '92, (coupled trap)
5. Carl Weimer, Anti-H workshop, Munich, July, '92, (positron source)

g. Other invited talks:

1. Wayne Itano, Harvard, Nov. '91.
2. Wayne Itano, U. Mass., Nov. '91.

3. Jim Bergquist, NIST, Boulder, colloq., Feb. '92.
4. Dave Wineland, NIST, Gaithersburg, colloq., March. '92.
5. Dave Wineland, colloq., IBM, Aug, '92.

h. Honors/awards/prizes/offices etc.

1. Chair, APS Division of Atomic, Molecular, and Optical Physics (DAMOP) (Dave Wineland)
2. Secretary-Treasurer APS Laser Science Topical Group (LSTG) (Wayne Itano)
3. QELS '92 Laser Spectroscopy Chairman (Dave Wineland)
4. Election to National Academy of Sciences (Dave Wineland)